NASA James Webb Space Telescope

Engineering of the Primary Mirror Segment Assemblies (PMSA) & the Primary Mirror Backplane Support Structure (PMBSS)

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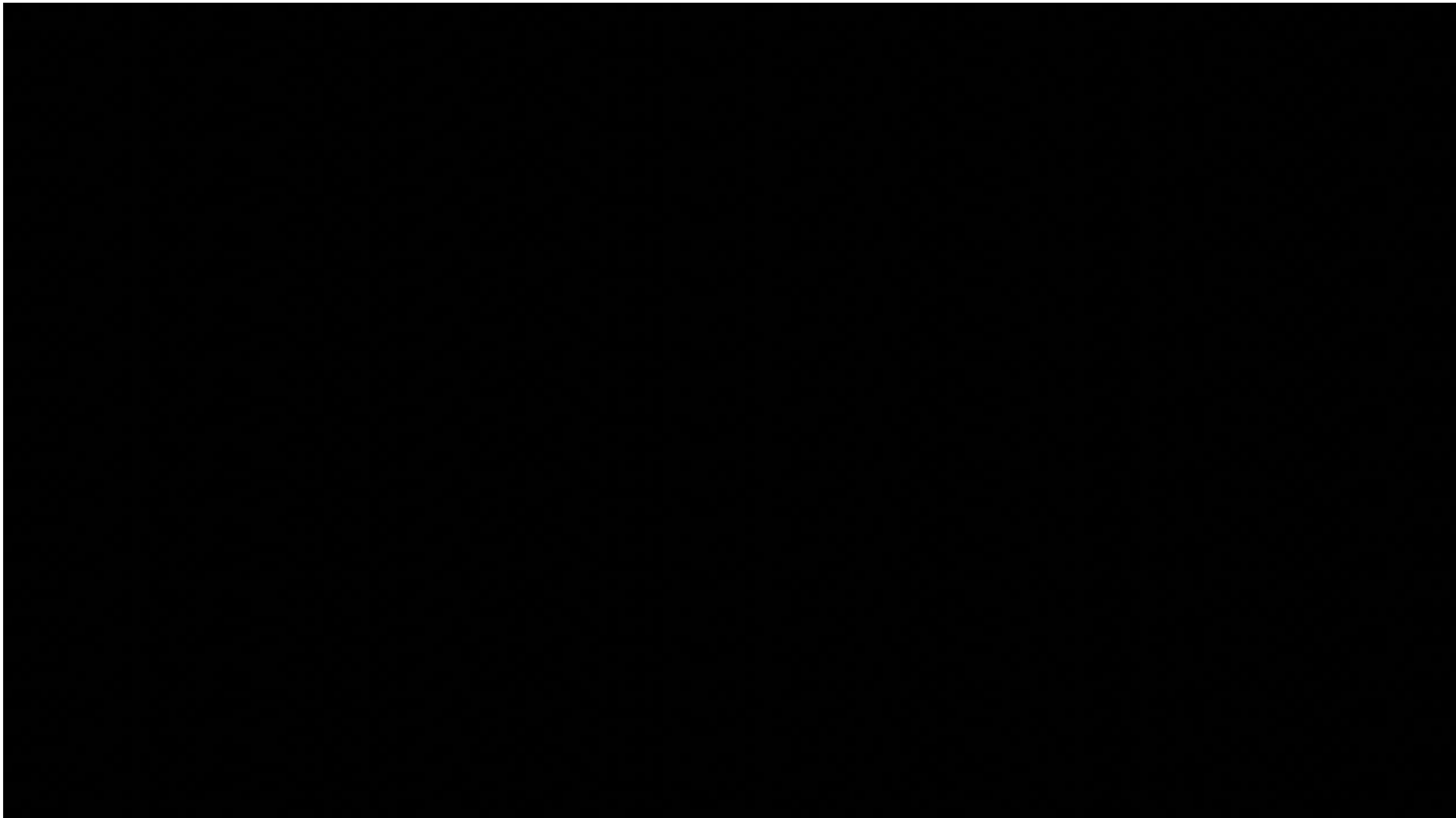
Intro-1



Intro-2

Intro-4

SCIENCE

Webb Telescope Science Themes

"The James Webb Space Telescope will be a giant leap forward in our quest to understand the Universe and our origins. JWST will examine every phase of cosmic history: from the first luminous glows after the Big Bang to the formation of galaxies, stars, and planets to the evolution of our own solar system."

First Light & Reionization

JWST will be a powerful time machine with infrared vision that will peer back over 13.5 billion years to see the first stars and galaxies forming out of the darkness of the early universe.

Read More

Assembly of Galaxies

JWST's unprecedented infrared sensitivity will help astronomers to compare the faintest, earliest galaxies to today's grand spirals and ellipticals, helping us to understand how galaxies assemble over billions of years.

Read More

Birth of Stars & Protoplanetary Systems

JWST will be able to see right through and into massive clouds of dust that are opaque to visible-light observatories like Hubble, where stars and planetary systems are being born.

Read More

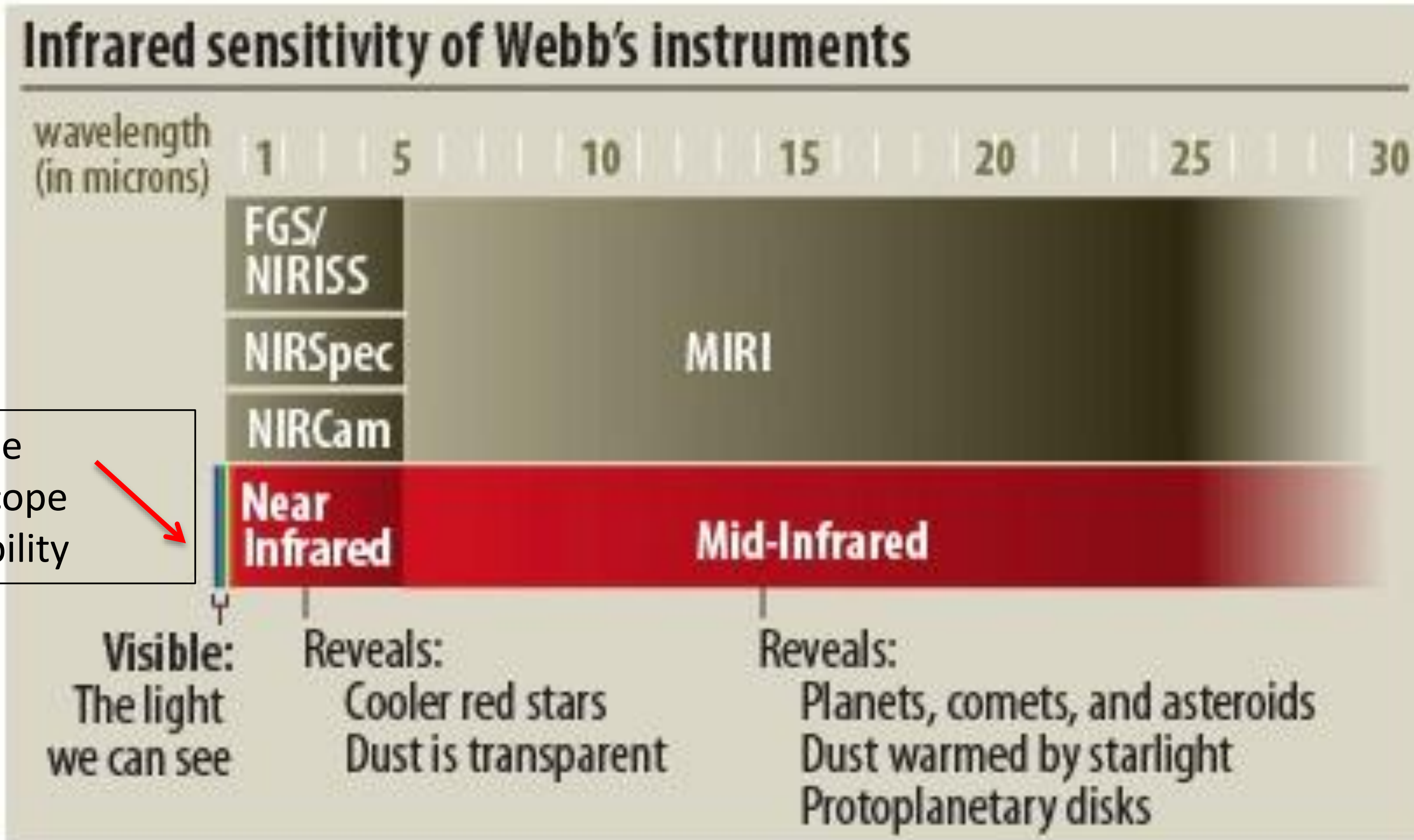
Planets & Origins of Life

JWST will tell us more about the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe. In addition to other planetary systems, JWST will also study objects within our own Solar System.

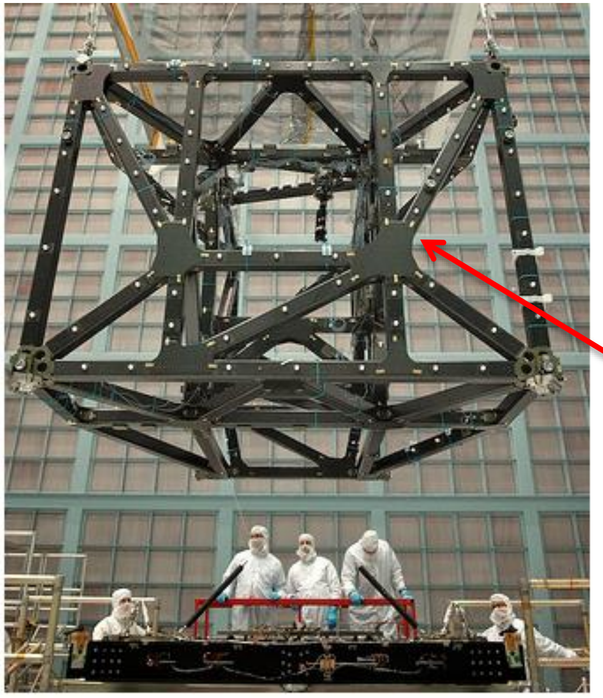
Read More

Spectrum Covered by the ISIM Instruments

Hubble Telescope Capability



Intro-3

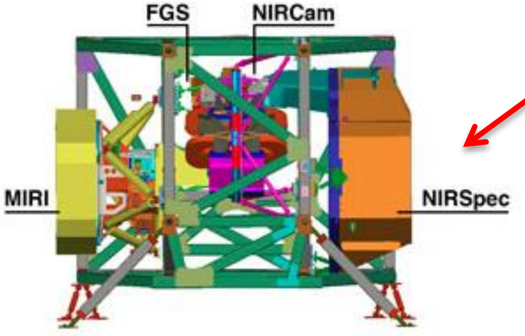


Integrated Science Instrument Module (ISIM)

Graphite Composite Structure That Holds the 4 Science Instruments

The ISIM includes the following instruments:

- Near-Infrared Camera, or NIRCam - provided by the University of Arizona
- Near-Infrared Spectrograph, or NIRSpec - provided by ESA, with components provided by NASA/GSFC.
- Mid-Infrared Instrument, or MIRI - provided by the European Consortium with the European Space Agency (ESA), and by the NASA Jet Propulsion Laboratory (JPL)
- Fine Guidance Sensor/ Near InfraRed Imager and Slitless Spectrograph , or FGS/NIRISS - provided by the Canadian Space Agency.



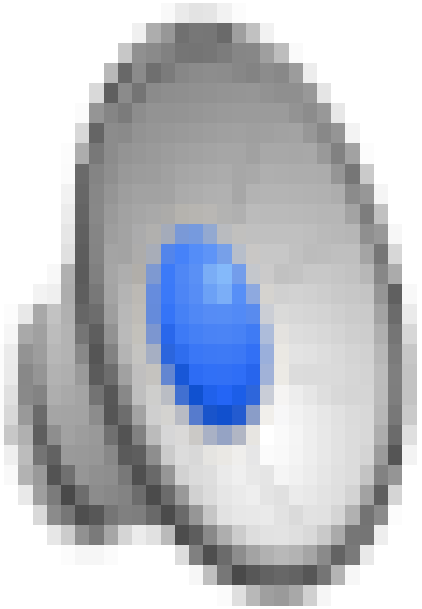
Now Onto The Engineering !!

Primary Mirror Segment Assemblies (PMSA) -1

(Ball Aerospace was the prime contractor for these assemblies)

- O-30 Beryllium Substrate
  - High Purity, Very Uniform Properties, Very Low Cryogenic Tangent CTE (~ 50 PPB/K @ 45K), Relatively Low Precision Elastic Limit (PEL) (~21MPa , so we limited the stress to approx 14Mpa), High Specific Stiffness.
- S-200 Beryllium “Whiffles” , “Delta Frame” & “Strong Back Struts”
  - Much Stronger Than O-30 & Higher PEL
- Titanium Flexures between the Substrate & the Whiffles
  - Needed to Provide High Strength & Flexibility
- 6 DoF Actuator Assembly to Align Mirror After Deployment (coarse & fine stage actuators allow minimum motion resolution of nm (10^{-9}m)
- Radius of Curvature (RoC) Actuator to Correct Final Radius of the Mirror So That All Mirrors Will Have Their Radii Match to Within +/-160um (out of 16m).

PMSA-2



PMSA-3

- Mirror Segment Manufacture- “The Blank Material”
  - Brush-Wellman Fabricates a Steel “Can” in the Shape of a Hexagon
    - The O-30 Powder Is Then Placed in the Can & The Can Is Subjected to a High Temperature Hot Isostatic Pressure Process (HIP). The Can is then removed by acid etching it away.
      - During the very first Can etching process, the beryllium blank cracked. SAO found that since the Can was only partially submerged in acid during the etching process, a great deal of local heat was created & large tensile surface stresses were created; enough to crack the beryllium. Once the etching process was modified to etch the entire can at one time, no failures were encountered.

PMSA-4

Half-etched Steel Can

Beryllium Blank

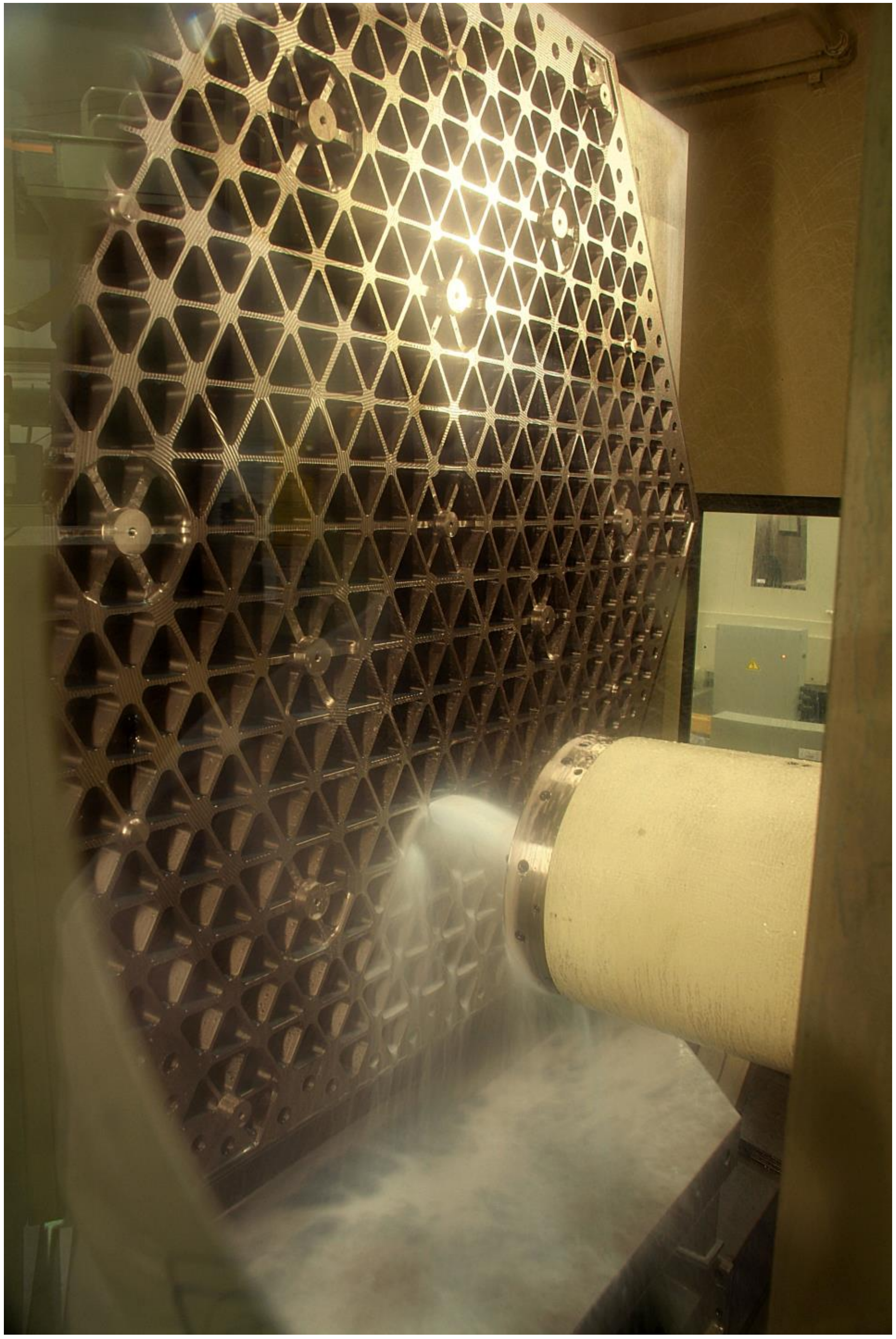
Crack

PMSA-5

- Mirror Segment Manufacture- Coarse & Fine Machining of the blanks
  - When the blanks finally end up looking like un-polished mirrors, the beryllium material has to be free (enough) of residual stress so that over long term (> 7 yrs) the mirror figure will not change (much).
    - Once the mirror segments were “roughed out” the pocketed back surface of the mirror was acid etched to remove a set amount of beryllium that was determined via a set of “residual stress” experiments. The optimum number of pockets was a trade-off between machining capability & machining time, RoC uniformity, and stress due to launch loads. The thickness of the face sheet was also optimized for these effects as well as effects of polishing (the so-called “print thru” effect)
      - FEM modeling of each PMSA consisted of full 3D shell & solid models of a few million DOF each using both linear & non-linear properties. These models were then used for all linear & non-linear analyses including launch, effects of residual stress, effects of creep & effects of temperature changes on-orbit, etc

PMSA-6

- O-30 beryllium creep experiments were performed at the Charles-Stark Draper Lab in Cambridge , MA. From this data, SAO developed the creep equations so that were to determine a limit on the max acceptable residual stress on the from surface of the machined mirror.
- This led to a set of complicated front surface machining operations related to how much material could be removed per pass, how often we had to replace the tools, and finally what sort of stress relieving would be necessary during the entire process.
  - High frequency vibration was found to remove ~1/4 of the residual stress that was removed during normal heat treating. So while this was much faster than heat treating it was not as effective & not used.



PMSA-7

- Machining Operations at AXSYS Technologies
  - 5 Axis Milling Machines Were Manufactured for this Purpose
  - The machines were so accurate that they could be used for in-situ metrology as well (um level).
  - Since Be is considered a health risk, all manufacturing at AXSYS Technologies was done in an enclosure.

PMSA-8

First Completed Mirror Substrate at AXSYS Technologies

PMSA-9

- The mirror blanks were then shipped to Tinsley Labs where they would become polished mirrors whose surface figure was < 25nm RMS over the 1.5m (point to point), 1.5m^2 surface area.
- This process consisted of coarse & fine grinding & then coarse & fine polishing. Both large scale (0.25m) & small scale (0.05m) tools were used for this processing. One ALWAYS had to think 1 or 2 steps ahead to make sure that the processing that would now take place would not hinder future processing. This is especially true during grinding when significant stress can be created.
- During the early grinding & rough polishing runs, metrology of the surface was performed with a CMM which had micron class resolution.
- When the surface of the mirror would be a few um P-V, interferometry was used from then until the final processing.
- The mirror was figured as if it were at ~45K but without actually ever having been at 45K.
  - After the first batch of mirrors was nearly completed at Tinsley, they were sent to the XRCF Facility at NASA/Huntsville where they were cryogenically tested.
  - From that test, cryogenic “difference” maps were created so that the mirrors could be sent back to Tinsley for final figuring.

PMSA-10

Computer Controlled Optical Surfacing (CCOS) Machine At Tinsley Labs

Tool

Mirror Substrate

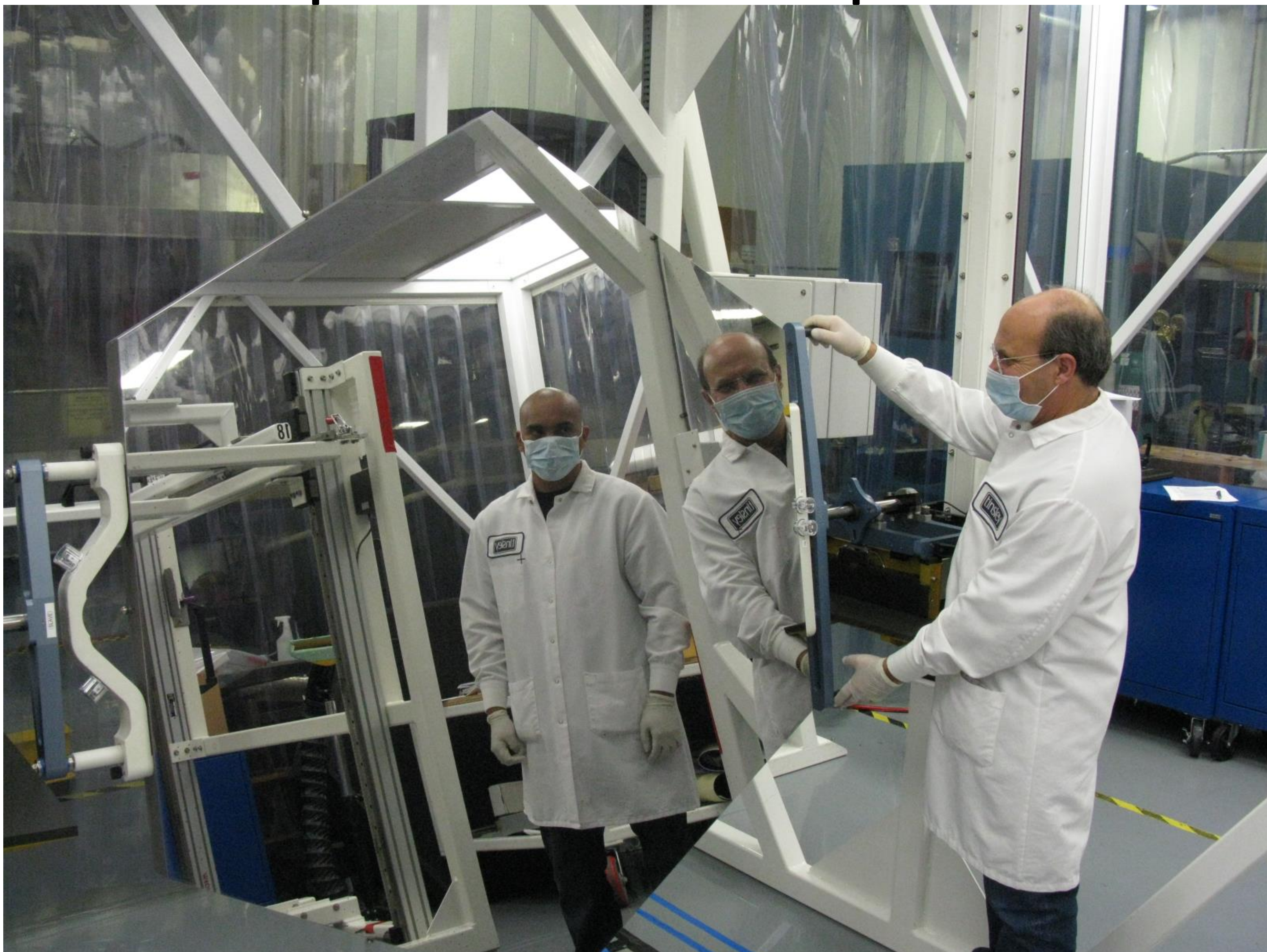
PMSA-11

Multiple CCOS Machines Being Operated At One Time

The facility was kept amazingly clean !

PMSA-12

Visual Inspection of Completed Mirror



PMSA-13

- The polished mirrors were then sent for coating at Quantum (QCI) for a proprietary, multi-layer gold coating
  - The coating had to be robust enough to withstand numerous thermal cycles from approx 345K to 30K , be able to withstand the rigors of launch acoustics & vibration as well as not introduce residual stresses (thru the coating process) that could creep-out.

- Once the mirrors were coated & assembled they were subjected to an 18-g sine burst test, a sine vibration test, random vibration and an acoustics test (only 1 of the 18) to show that the change in their figure was within acceptable values (a few nm RMS change in both figure (non-astigmatism) & perhaps 10nm RMS of astigmatism. Astigmatism can be removed in each optic by using the 6 DOF actuators and "decentering" the optic.

PMSA-14

Sine Vibe Normal to Mirror Surface

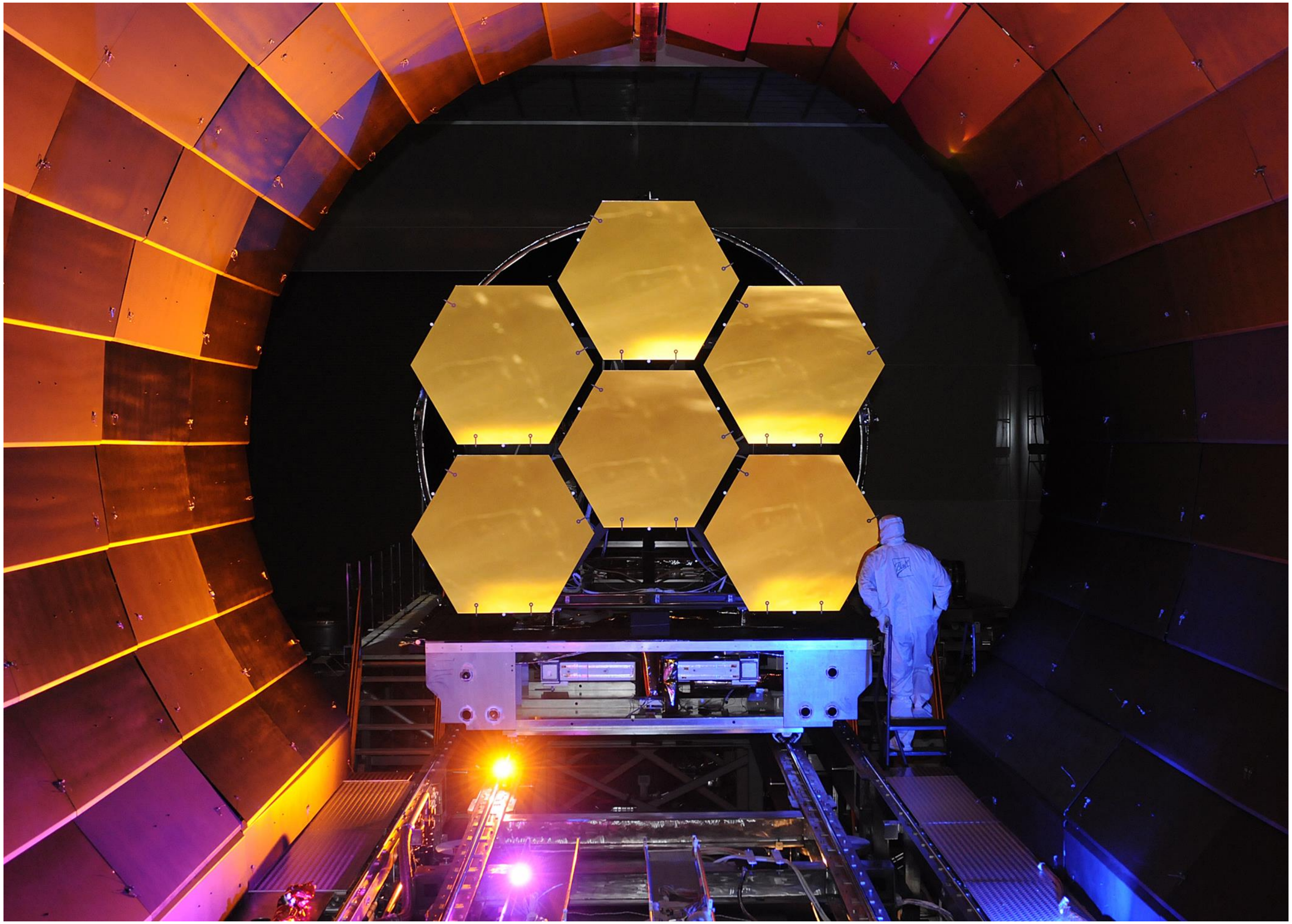
PMSA-15

- Once the mirrors were “finished”, they were sent again for cryogenic testing at NASA/MSFC for “buy off” of the cryogenic figure.

- Then the optics were shipped to NASA/GSFC to await final integration onto the PMBSS (Fall ‘15).

PMSA-16

Final Cryogenic Testing of 6 Gold Coated PMSA's @ NASA MSFC



Primary Mirror Backplane Support Structure (PMBSS) -1

(ATK was the prime contractor for this structure)

- This structure supports the 18 flight PMSA optical assemblies, the Aft Optical Assembly (which contains the Tertiary & Fine Steering Mirrors), interfaces with the deployable Secondary Mirror Support Structure, interfaces with the ISIM and finally interfaces with the Spacecraft.

- The PMBSS has to be strong enough to support its payload during launch, not fail at cryogenic temperatures (or transitions between RT & 30K) and be stable (enough) on orbit so that when the pointing of the telescope changes, the ~0.2K dT change in the structures temperature environment will not change the telescopes Wave Front Error (WFE) more than ~50nm (or 25nm surface across a 6m+ structure).

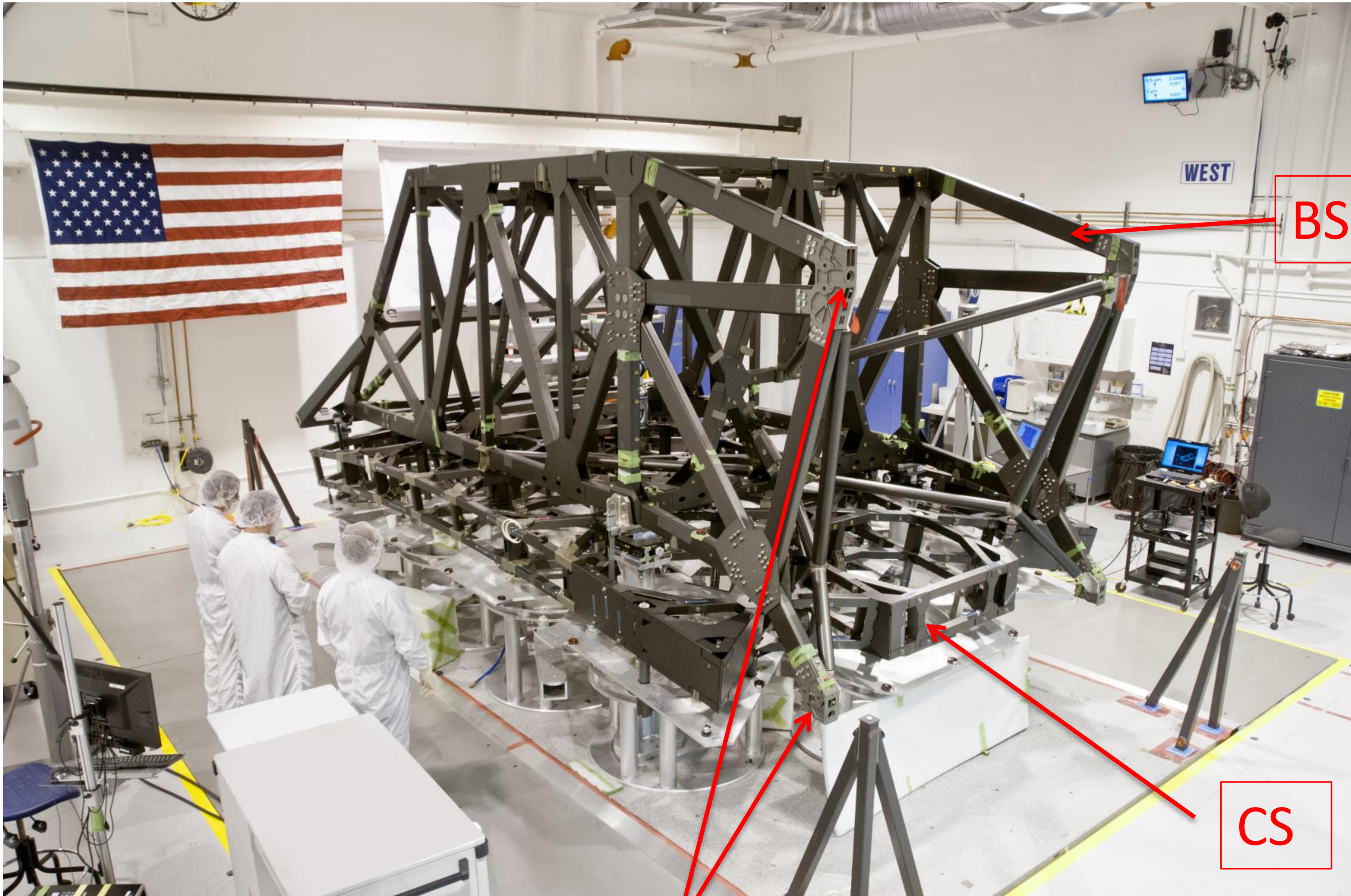
PMBSS-2

- The PMBSS is built using M55J/954-6 composite tubes & plates and where greater strength is necessary parts had layers of T300 added. Invar 36 metallic parts are used where thermal stability is required. Titanium is used where high strength is required.
- Epoxy bonding, epoxy bonding + metallic fasteners & metallic fasteners only are used to construct the PMBSS. To get the structural elements to work together at BOTH room temperature (launch) & cryogenic temperatures (on orbit), the process did require development of new analytic techniques & a better understanding of the different failure mechanisms.
- Material allowables were developed for temperature ranges from 30K to approx 350K. This includes allowables for the composites, invar, titanium & epoxy. Due to the robustness of the analysis & test program we were able to use lower Factors of Safety on the thermal loads (~1.07 vs. 1.5)
  - FEM models of these tests were correlated w/ the actual test results

PMBSS -3

Center Section (CS) Only Shown Prior to the Backplane Support Frame (BSF) Being Installed

PMBSS -4
CS & BSF Fully Mated



Titanium Spacecraft Interface Fittings (2 sets)

PMBSS -5

- Solid 3D FEM models were created that could be used for:
  - Stress analysis at 293K +/-
  - Thermal distortion analysis from cryogenic temperatures to post-launch temps (where there was low inertial loads but “high” temperatures)
- Separate, highly localized, more refined 3D stress models were created for cryogenic conditions or where high normal tension (peel) stresses were high (even at non-cryogenic temperatures.

- Strength testing of sub-scale test articles (but which had all of the features of the flight hardware) showed excellent agreement with the composite interaction curves that were developed. Failure load was accurately predicted.

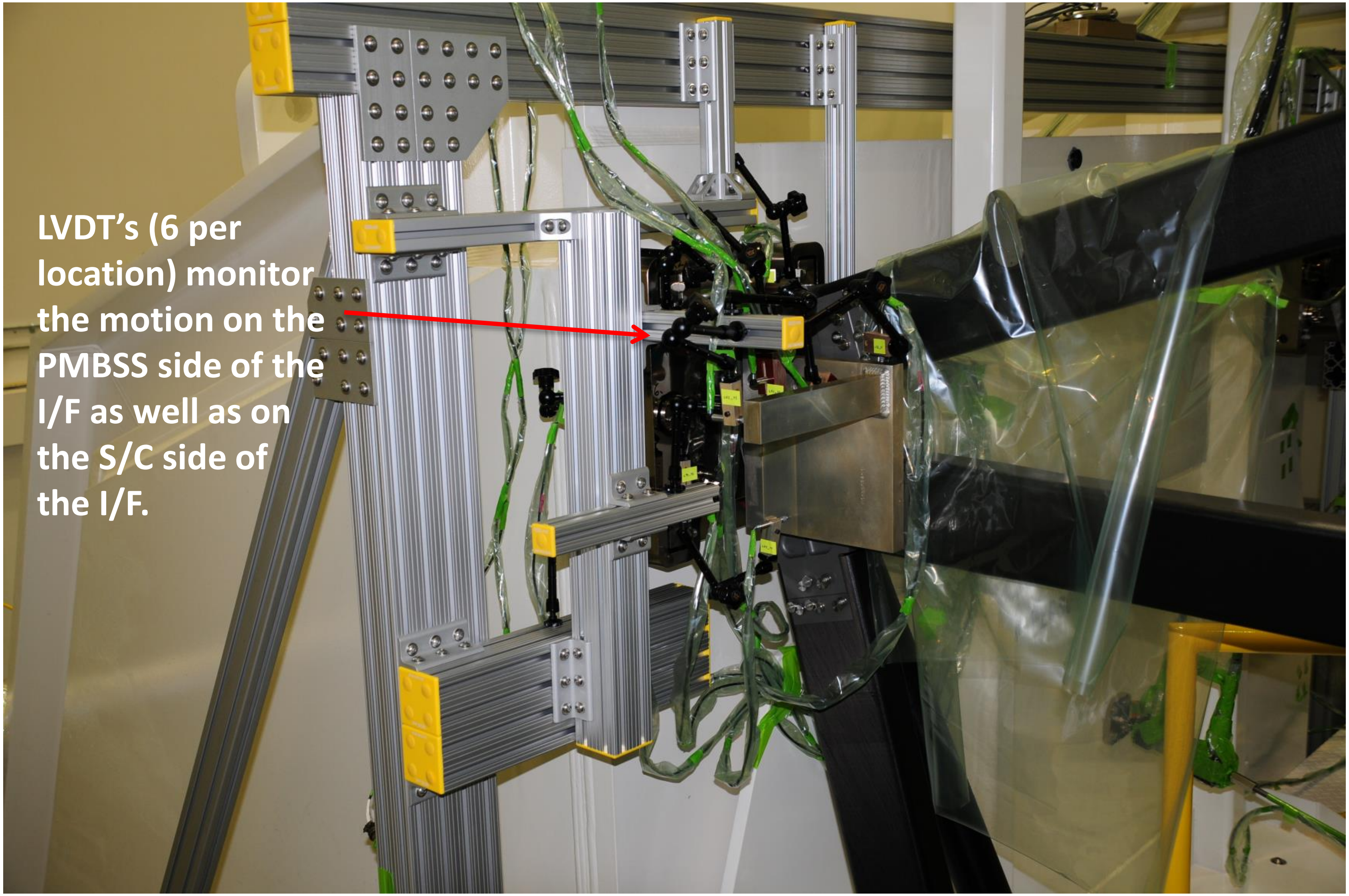
PMBSS-6

- Following assembly of the PMBSS it was sent to NASA/MSFC (same facility used to cryogenically test the PMSA's) for cryo cycling to make sure:
  - No failures would occur
    - This also served to validate our stress models to show how non-uniform the structure temperature would allowed to be in flight during cool down
  - Reference location relative motions moved less than specified
- No failures occurred, as verified by ultra-sonic inspection & all metrology measurements (during the test) were within expected values.
- Now on to strength testing !

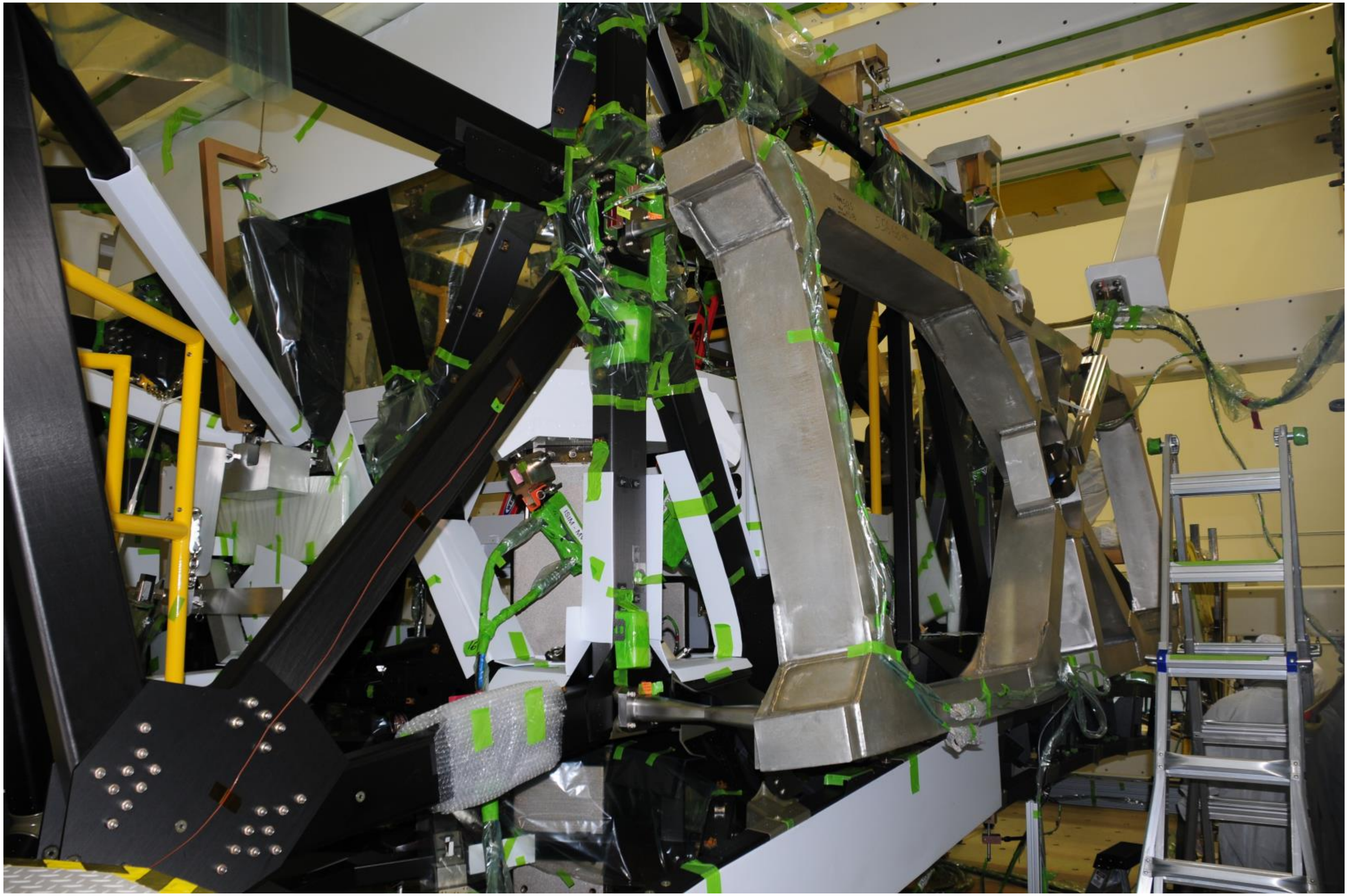
PMBSS-7

- Each and every interface (I/F) on the PMBSS had to be tested to 1.25 its Design Limit Load (DLL). These loads were separated into two distinct types of loads:
  - LIAL- Local Interface such as the loading that a PMSA (~40kgs) subjects its I/F on the PMBSS to.
    - These loads were developed earlier in the program and in general are more conservative than the GIL loads. These loads may be a few thousand Newtons
  - GIL- Global loads such as when all of the PMSA are being accelerated in the same direction at the same time. These loads are typically > 100,000N
- The PMBSS was supported at the 4 Spacecraft I/F points during all of these tests.
  - Tests were monitored w/ LVDT's & strain gauges

PMBSS-8


LVDT's (6 per location) monitor the motion on the PMBSS side of the I/F as well as on the S/C side of the I/F.

PMBSS-9



Loading Devices Attached to the Wing I/F's

PMBSS-10

Real Time Strain & LVDT (Displacement) Monitoring

PMBSS-11

- Following two of the GIL tests, we found that LVDT’s located near the far end of the structure (away from the S/C support points) were reading ~25% higher than expected. (This “could” have implied that the stiffness of the structure was 25% lower than expected.) We had not known how influential the stiffness of the S/C fitting area was at the time.
- We added > 60 LVDT’s to monitor the interface on the “other” side of the S/C I/F. We found that we were seeing motions of order 0.2mm; much greater than expected.
- We were able to create a matrix of I/F motion points and apply them back to the S/C I/F and when we did that the error between our FEM & the test results dropped to ~7%. These calculations were done by two different organizations using two different methods & they both agreed to ~2% absolute.

PMBSS-12

- The ONLY failure that we encountered was when a technician "ran" into a bracket and applied ~4X the DLL load. Besides that bracket failure (which has been fixed & retested) there have been no failures on any of the PMBSS hardware.

- The PMBSS arrived at NASA/GSFC in late Aug 2015 and will start its integration of the flight hardware.

Full Scale Demo Testing (FSDT)-1

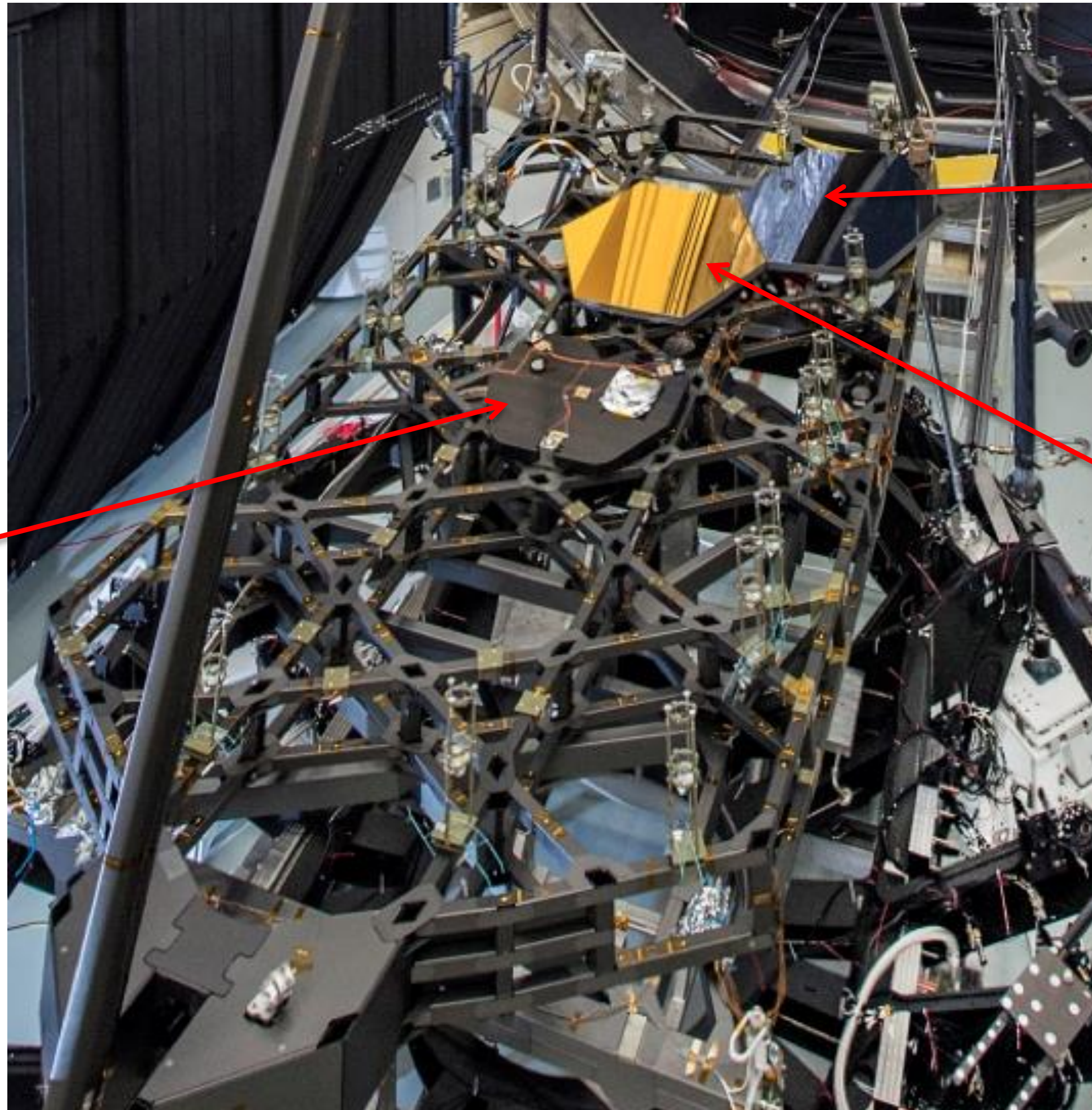
- Engineering demonstration units of the PMSA's & PMBSS (Center Section only) were fabricated by each systems' contractor. These units showed that not only could the flight units be manufactured to its requirements but that it could be properly assembled.
- A demonstration program termed OGSE (Optical Ground Support Equipment) was set up to combine the two non-flight spare mirrors, the Pathfinder structure (PMBSS center section only) & the backup Secondary Mirror Assembly. These components were successfully assembled & then transported to NASA/JSC where they would be subjected to a cryogenic test (~32K).

FSDT-2

- After the unit under test (UUT) was brought down to 32K, the two non-flight mirrors were phased to one another to “tens of nm”. This showed that when the telescope is in orbit we will be able to successfully phase all 18 mirror segments.
- This test was also meant to prove out our ability to measure the change in figure of the structure as the temperature was changed by a few K.
  - For this so-called Thermal Distortion test, SAO developed “Piston Sensors” . These optical assemblies were placed around the perimeter of the structure to measure the change in figure of the structure over a 2.5K dT; >10X what is expected on-orbit.
  - Due to higher than expected vibration, we were unable to use the Piston Sensors but did get reliable results from the change in tilt between the two mirrors. OGSE-2 testing will give us a second chance at the TD testing with much less vibration.

FSDT-3

Aft Optics Assembly Mass Simulator. Used To Apply 1.25X The Weight Of The Flight AOS Which Will Be Used Here During OGSE-2.

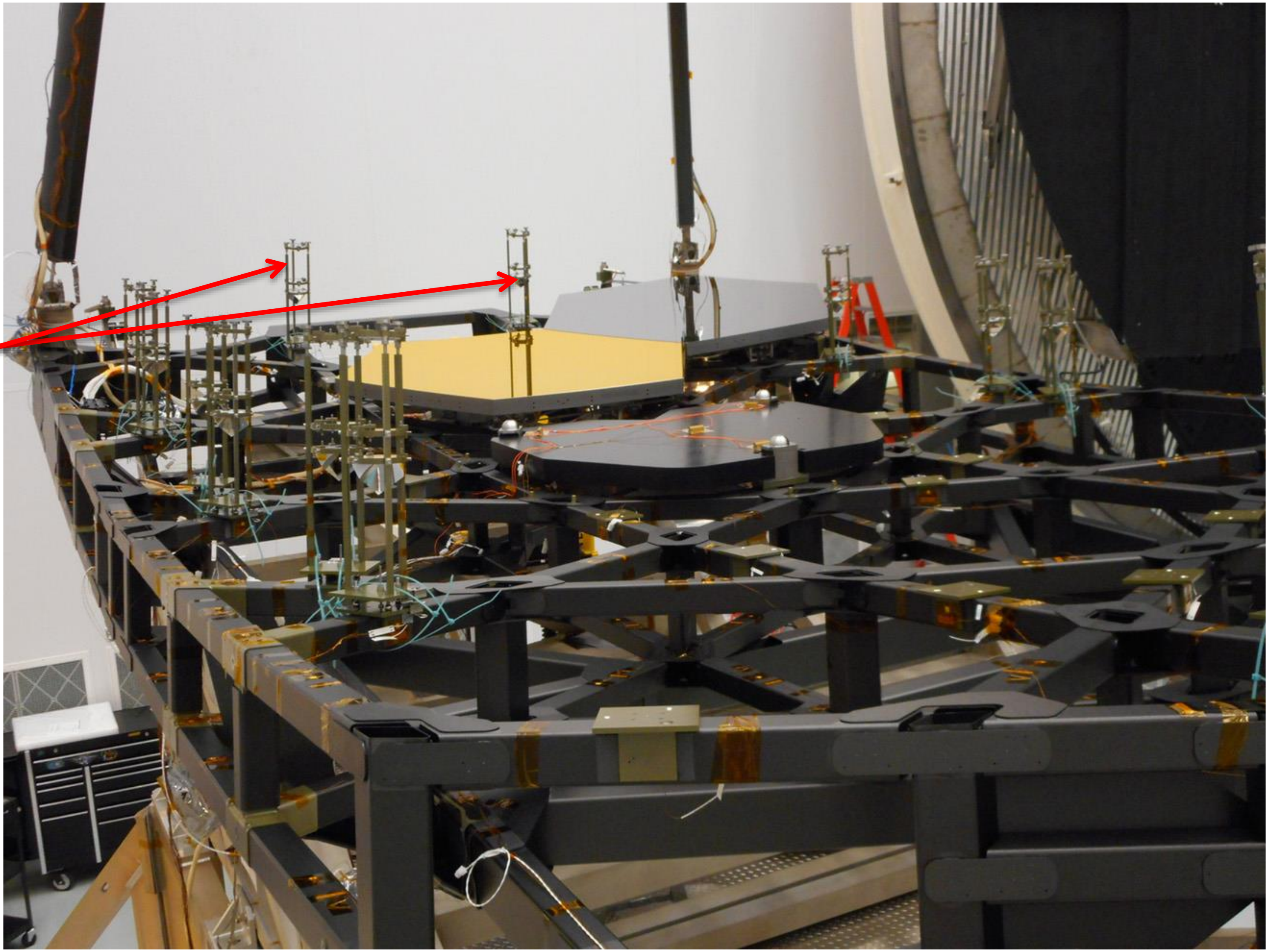


Non-coated Spare PMSA

Gold Coated Engineering Demo Unit (EDU)

FSDT-4

SAO-Designed & Built Piston Sensor Assemb-lies (Qty 16)



Summary

- The design, engineering & tests of the PMSA’s & PMBSS show that we have a robust system that not only meets but exceeds (better than) the design requirements for these components.

- In the next 2 years the Telescope & Observatory will be subjected to a simulated launch environment (sine vibe/acoustics) and operations tests at cryogenic temperatures.
- Launch is schedule for the last quarter of 2018 !

- *Ad Astra Per Aspera (The fewer the better !)*

Notes:

- SAO is supported by a grant from NASA/GSFC (NNX13AI83A S12).
- Thanks to the observatory contractor Northrop Grumman & the major subcontractors Ball Aerospace & ATK (now Orbital ATK) for their effort on this fantastic Observatory as well as all of our colleagues at NASA & for providing input to this talk.
- Thanks to the team at SAO (Michael Eisenhower & Vladimir Kradinov) who really did much of our work on the PMSA’s & PMBSS respectively.